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(Statement A)

THE USAF ELECTRIC PROPULSION RESEARCH PROGRAM*

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Abstract

An overview of current electric propulsion research and development efforts within the United States Air Force is presented. The Air Force supports electric propulsion primarily through the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL) and the AFOSR European Office of Aerospace Research and Development (EOARD). Overall direction for the programs comes from Air Force Space Command (AFSPC), with AFRL mission analysis used to define specific technological advances needed to meet AFSPC mission priorities. AFRL mission analysis used to define specific technological advances needed to meet AFSPC mission priorities. AFOSR funds basic research in electric propulsion throughout the country in both academia and industry. The AFRL Propulsion Directorate conducts electric propulsion efforts in basic research, engineering development, and space flight experiments. EOARD supports research at European laboratories that feeds directly into AFOSR and AFRL research programs. Current research efforts fall into 3 main categories defined by the thruster power level. All three agencies are conducting research at the low-power regime ($P < 200$ W), in support of emerging USAF microsatellite missions. Emphasis on research in the mid-power range (500 W to 5 kW) is diminishing with the near-term conclusion of the 4.5 kW Hall thruster development program, and the high degree of commercialization in this power range. The high power regime ($P > 30$ kW) is realizing increased emphasis through such programs as a collaborative AFRL research effort with industry.

I. Introduction

To provide enhanced spacecraft maneuvering capability at reduced cost, the United States Air Force (USAF) has developed a coordinated research program within the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL), and the AFOSR European Office of Aerospace Research and Development (EOARD). Overall guidance for these research efforts comes principally from Air Force Space Command (AFSPC) in the form of a Strategic Master Plan (SMP). The SMP provides a 25-year USAF plan, detailed in terms of near-term (2000-2007), mid-term (2008-2013), and far-term (2014-2025) development priorities. AFRL and AFOSR perform mission analysis to determine the optimal propulsion systems for AFSPC missions, and then promote research programs to develop the technologies needed to achieve these missions. EOARD interacts

with AFRL and AFOSR to develop research at European laboratories that feeds directly into the AFOSR and AFRL research programs. Near-term missions are generally served through commercial contracts at the System Program Office (SPO) level. The AFRL role in these decisions is primarily one of technical advice, advocacy, and demonstration of new technologies to facilitate technology transfer to the commercial sector. The research role of AFRL and AFOSR is focused on the mid- and far-terms, with AFOSR directed more towards performing the basic research that enables AFRL to meet the far-term mission needs via a future advanced engineering program.

The AFRL technology development advances are baselined and measured through the Integrated High Payoff Rocket Propulsion Technology (IHPPT) program. IHPPT is an all-encompassing propulsion development program, which details specific

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performance advances for each technology area in a three-phase effort from 1995 to 2010. The IHPPT baselines and goals were determined through a collaborative effort between AFRL, NASA and industry. All current AFRL electric propulsion funding falls under the guidance of the IHPPT program.

Although a majority of the resources are used for conventional core funding and in-house research, AFOSR and AFRL also manage a number of contracts through the Small Business Innovation Research (SBIR) and the Small-Business Technology Transfer Research (STTR) programs. Contracts under the SBIR/STTR programs are also directed towards achieving the IHPPT goals. In all efforts, the USAF organizations coordinate their respective research programs so as to maximize effectiveness in achieving the AFSPC priorities and the IHPPT goals.

Historically, USAF electric propulsion research has been directed primarily at medium power technologies (500W - 5kW) for stationkeeping, rephasing, and orbit topping applications. Electric propulsion in this class is largely commercialized. Both arcjets and ion thrusters are now seeing widespread use on commercial satellites, indicating their availability for military applications. The exception is the Hall thruster. Whereas the Hall thruster has performance characteristics (specific impulse, thrust density) optimal for the on-orbit USAF satellite missions, it has only seen widespread operational use in Russia. To promote the domestic commercialization of the Hall thruster, AFRL is co-funding the development of a 4.5 kW High Performance Hall System (HPHS) in a cost shared contract with International Space Technology Incorporated (ISTI) with Atlantic Research Corporation (ARC) as the prime contractor. The HPHS has demonstrated performance in excess of the IHPPT Phase I goals. The final major task is a 7200-hour life test of the qualification model thruster, scheduled to start in December 2001 at AFRL.

Following the completion of the 4.5 kW HPHS program, AFRL and AFOSR research emphasis on mid-power thruster technologies is expected to decline. The technology should be of sufficient maturity, and the commercial payoffs sufficiently large, that further performance advances would be accomplished most effectively in the private sector. Opportunities continue for research that abets the Hall thruster commercialization by decreasing perceived risk associated with spacecraft interactions. AFRL and AFOSR are pursuing efforts to better

understand the spacecraft-plume interactions through modeling and simulations, supported by laboratory and space measurements where possible. AFRL has contracted an effort with General Dynamics to decrease spacecraft interaction through the use of physical plume shields between the thruster and critical spacecraft surfaces. The USAF spacecraft interaction research programs are grouped into the high-power range for this paper, however it is clear that the results will have comparable impact across the power ranges. For the modeling and simulation efforts, the payoff will likely be strongest at the high-power regime where ground-based measurements are more significantly perturbed by test chamber effects.

With the projected decline in electric propulsion research for the mid-power range, the USAF emphasis has bifurcated toward the low-power (< 200W) and the high-power (> 30kW) regimes. Low-power electric propulsion research responds to the AFSPC priority for highly maneuverable microsatellites performing Modular On-Orbit Servicing (MOOS) or flying in formation to enable missions such as a sparse aperture Space-Based Radar (SBR). Mission analysis shows that both high specific impulse and high thrust micropropulsion will be required to meet the low-power AFSPC missions, and the USAF is pursuing research in both areas. High-power electric propulsion research responds to the AFSPC priority for Orbit Transfer Vehicles (OTV) and the propulsion capability to rescue and reposition marooned assets that failed to achieve final mission orbit. Although not described within this paper, AFRL also supports in-house and contractual research in solar-thermal spacecraft propulsion directed towards enabling the same AFSPC high-power missions.¹

AFOSR supports industry and university research in low-power regime technologies such as colloidal thrusters, low power Hall thrusters, Laser Plasma Thrusters and Pulsed Plasma Thrusters (PPTs) for the high specific impulse maneuvers, and research in digital chemical microthrusters for the high thrust maneuvers. EOARD supports 40W - 100W Hall thruster research in Russia, and 100W resistojet research at Surrey, UK. AFRL supports 200W Hall thruster, PPT development, laser-plasma thruster engineering, and electrodynamic tether development, often co-funding these efforts with AFOSR. EOARD and AFRL support separate research efforts in low-power, low-propellant, neutralizer technologies, essential for a low-power Hall thruster or a microsatellite-sized Tether system. In-house research at AFRL, partially funded by AFOSR, has focused on

miniaturized versions of the PPT and miniaturized chemical motors for high-thrust maneuvers.

A major part of the AFRL micropropulsion effort is the development of a low-power propulsion system for the TechSat21 spacecraft, scheduled for launch in 2003. The contract for the primary propulsion system on TechSat21 has been awarded to TRW for a 200W Hall thruster that will demonstrate IHPPT Phase II goals for electrostatic spacecraft propulsion. TRW is subcontracting the thruster development to Busek and the propellant feed systems to Moog. The Busek 200W Hall thruster was originally developed under AFRL and AFOSR SBIR contracts. A second AFRL effort on TechSat21 will be to demonstrate micropropulsion for attitude control using the AFRL MicroPPT. The MicroPPT developed for TechSat21 will demonstrate the IHPPT Phase II goals for electromagnetic spacecraft propulsion.

The high-power regime is realizing increased research emphasis. AFRL has entered into a commercial partnership to research the effects of assembling several Hall thrusters into a clustered array to achieve high total system power. This follows a year of discussions with industry, universities, and government users to determine the most efficient means of achieving high power electric propulsion capability while minimizing total lifecycle costs. Ongoing AFOSR basic research on Hall thruster physics at the universities has beneficial impact both at the mid-power regime and the high-power regime.

In the following sections, various research programs supported by AFRL, AFOSR and EOARD are summarized with references to more complete descriptions. Summaries of the AFOSR funded efforts at the universities can be found in a companion paper from this same recent conference.²

II. Low Power Electric Propulsion (< 200W)

100 Watt Hall Thruster

AFOSR's European Office of Aerospace Research and Development (EOARD) is in the process of initiating two projects with Russian institutes investigating Hall thrusters. Last year, EOARD funded Fakel Design Bureau, Kaliningrad, Russia for the development of a 100W Hall thruster and "heaterless" hollow cathode that could operate for up to 1000 hours of operation. At 94.5W, the thruster generated 4.7mN thrust at an Isp of 1000 sec and efficiency = 24 %. Building on last year's work, EOARD is funding the Kurchatov Institute, Moscow,

Russia to create a detailed database of the plasma parameter distributions for the same small (SPT-25) hall effect thruster that addresses: transverse accelerated ion distributions, energy distributions for ions flowing out at different angles to the thruster axis, fraction of multicharged ions flowing out at different angles to the thruster axis, and the concentration of neutral atoms in the plume.

Ablative Pulsed Plasma Thruster (APPT)

The Kurchatov Institute will also study the physics of APPT operation. The main tasks for this effort are: develop adequate physical-mathematical and calculative models of the APPT operating process, study energy flux into propellant surface in the range (10-100) J energy release by determining the mechanism of energy flux transfer to propellant surface, investigate the current sheet dynamics in APPT in the range (10-100) J energy release, study ablation delay time effects, optimize the accelerating channel geometry to reduce the delay time ablation, study the heat transfer in propellant under pulsed operation, study the efficiency of energy conversion in APPT with a monitoring of the propellant flow rate in order to save propellant mass.

Field Emission Diamond Cathodes

Busek Co. is currently funded under an AFRL Phase II SBIR Program to develop a diamond based field emission (FE) cathode for space propulsion applications. Motivation for a field emission cathode stems from the deleterious impact of hollow cathodes on the performance (efficiency and Isp) of low power electrostatic thrusters including Hall and ion thrusters. The FE cathode is also a candidate for neutralization of the colloid and FEEP thruster beams.

The Phase II effort focuses on the development of cathode emitter materials and cathode designs with sufficient current density to provide discharge and neutralization electron current for a 100 W class Hall thruster, such as those developed in Russia through EOARD. Several materials and fabrication techniques are being investigated. Material emission requirements are influenced by total current, cathode size, and space charge limits. Contractor analysis has resulted in a baseline design for a 1 Amp, 10 cm² emission area. The maximum electron current density is governed by the Child-Langmuir space charge equation. At V_a = 20 volts and d = 3.5 micron, the maximum current density is approximately 17 A/cm². The electron current density in the contractor design

is presently orders of magnitude less than the Child-Langmuir limit.

Coaxial Pulsed Plasma Thruster

CU Aerospace, teamed with the University of Illinois at Urbana-Champaign and Unison Industries, previously designed, fabricated and tested an electrothermal PPT-8 breadboard demonstrator. PPT-8 is a three-module coaxial side-fed pulsed plasma thruster that was designed based upon research of the single-module thrusters PPT-4³ and PPT-7⁴. The thruster uses side-fed Teflon bars, and is driven by low-loss mica capacitors at 100 W to produce a high-thrust greater than 2 mN. The PPT-8 research and development was funded by an AFOSR Phase I STTR, AFRL core funding, and the AFOSR TechSat21 initiative. Research and development of the Unison electronics were funded by NASA Glenn on an advanced PPT components development program.

An AFOSR Phase II STTR for the CUA effort was awarded for further development. Versions PPT-10 and PPT-10.1 are breech-fed, lightweight coaxial thrusters with a higher electromagnetic thrust fraction to achieve higher specific impulse (800 s) at a minimum 2 mN thrust. Thruster energy is 40-80 J at 80 W, and shot-to-shot repeatability is $\pm 2\%$. These designs will have a significantly higher fuel to thruster head weight ratio, approximately 50% rather than the 15% of the PPT-8 system. Testing with PPT-10 is producing results traceable to PPT-7 performance measurements. At the conclusion of the program, the thruster is expected to be in an advanced state of engineering development, suitable for incorporating into a future spacecraft flight integration effort with minimal additional engineering.

MEMS Mega-pixel micro-thruster

A new micropropulsion concept called the MEMS Mega-pixel micro-thruster array intended for stationkeeping of small and micro satellites is being developed and tested by the Honeywell Technology Center and Princeton University's Electric Propulsion and Plasma Dynamics Lab. The effort is supported under an AFOSR STTR contract. The thrusters have very low power and energy thresholds for ignition (~ 10 mWatts, ~ 100 μ Joules), and no moving parts. The array contains a quarter of a million separate thrusters on a 1.3" x 1.3" silicon die; the thrusters themselves are laid out on a 512 by 512 grid with 51 μ m by 51 μ m pitch. Each thruster has its own heater filament, which is co-axially aligned to a

hollow fuel-filled cavity directly above it. Each thruster/pixel is individually addressable and ignitable. The goals of the project include: 1) modeling the mechanical and thermal properties of the structures, 2) building the micro-thruster arrays, 3) measuring the performance of the thrusters using Princeton's new micro-thruster stand, and 4) advancing the fundamental understanding of how explosions occur in very small structures.

The following tasks have been accomplished successfully under this effort: 1) numerical modeling of the structures, 2) processing the igniter wafers, 3) building walls around the individual igniters, 4) coating the filaments with a Self-Assembled Monolayer (SAM) to facilitate good wetting by the lead styphnate (which will serve as the thermally-detonatable first stage), 5) preparing and applying the lead styphnate igniter suspension to the igniter filaments, 6) creating the hollowed-out cavity wafers, 7) bonding the styphnate-coated filament wafers to the cavity wafers, and 8) mounting the 2-layer structures onto appropriate packages, and 9) loading the cavities with nitrocellulose fuel at the Atlantic Research Corporation. The current status is that testing has been completed at Princeton and the results are presently being evaluated.

Laser Plasma Thruster

A Laser Plasma Thruster is currently in development in a joint effort between Photonic Associates (PA), Albuquerque, NM and the University of New Mexico. The research is led by Dr. Claude Phipps of Photonics Associates. The primary funding is through an AFOSR STTR contract with a smaller amount from AFRL for engineering development.

The Laser Plasma Thruster takes advantage of the recent commercial availability of 4-watt diode lasers with sufficient brightness and 100% duty cycle to produce a repetitively-pulsed or continuous vapor or plasma jet on a surface in vacuum. The diode is a low-voltage device (3V) with electrical efficiency in excess of 50%. A lens focuses the laser diode output on a 100- μ m diameter spot on the transparent side of a specially-prepared fuel tape. Passing through the tape without damaging it, the beam heats a specially prepared absorbing coating on the opposite side to high temperature, producing a miniature jet that generates thrust. The minimum impulse bit is 1 nano-N-s in a 100 μ s pulse. Thrust-to-optical-power ratio (Cm) is 50 to 100 μ N/W and typical specific impulse (Isp) is 500 seconds. Typical thrust at 4W optical power is 250 μ N. Mass of the preprototype and

associated electronics is 850g. Prototype mass is expected to be 700g, including 80g of expendable ablation fuel. Lifetime impulse is expected to be 250 N-s. Nominal tape speed is 6mm/s.

A pre-prototype Laser Plasma Thruster is currently undergoing performance measurements at UNM. The thrust stand is a torsion balance with design response of 0.26 mrad/ μ N, providing significant displacement for the 250 μ N thrust level of the LPT. An optical data link sends commands and receives data from the thruster microprocessor and a complete graphical user interface has also been developed. Previous performance data was based on single-pulse measurements on a more sensitive torsion balance. Data taken with the new test setup demonstrates that continuous operation behaves as predicted by the single-pulse data. Further performance tests are scheduled for Fall 2001 at AFRL in order to validate the UNM/PA thrust stand design.

Electrodynamic Tethers

For several years AFRL has expressed an interest in tether development since the propulsion application of these devices have the potential for significant reductions in total system mass. System analysis by AFRL for a LEO application has shown that an electrodynamic tether can deliver a total impulse divided by wet mass that is more than a factor of 10 greater than a LES 8/9 Pulsed Plasma Thruster. The predominant technical issues that need to be resolved are low mass electron sources and tether lifetime. The inherent complexity and risk associated with deploying and operating a tether can only be diminished through a flight demonstration.

In the past year AFRL Propulsion Directorate (AFRL/PR) contracted a tether development effort with Tethers Unlimited Incorporated (TUI) of Lynwood, Washington. Under the contract TUI will design and develop a relatively short (3-4 km) multistrand HoyTether™ appropriate for use on a microsatellite. Teamed with AFRL Space Vehicles (AFRL/VS) and NASA Marshall Space Flight Center, the system will be proposed as a secondary payload on upcoming AFRL/VS microsatellite flights. Current support to TUI is through an AFRL/PR Phase II SBIR contract. If the proposed flight manifestation is secured, core funding from all three agencies will be used to deliver the flight hardware.

The AFRL/PR technical objectives of the proposed flight are to: (1) Demonstrate functionality of a tether system through successful deployment and operation,

(2) Characterize tether survivability to orbital debris impacts which limit the tether lifetime in LEO, and (3) Demonstrate a low-mass electron source to enable the tether system to be competitive with other microsatellite propulsion options in terms of total system mass. The formal proposal for a microsatellite flight as a secondary payload is currently scheduled for January 2002. If the tether system is manifested on the microsatellite, launch is currently scheduled for 2004.

Micro-PPT

The past year has witnessed a significant shift in the AFRL emphasis on MicroPPT development⁶. To date the preponderance of USAF resources have been spent at the basic research level developing new MicroPPT designs with further reductions in dry mass. With the emergence of a flight opportunity on TechSat21 the MicroPPT research has grown to include significant emphases on engineering development.

MicroPPT engineering has focused on advancing earlier and simpler MicroPPT designs to flight status, in particular, by increasing reliability and lifetime while decreasing system mass. Performance is considered of secondary importance for two reasons. First, PPT thrust has historically been a simple function of discharge energy, with minimal variations from a linear dependence over 3 orders of magnitude. Second, if the thrust-to-power for an optimized MicroPPT is lower than that of a standard PPT, the impact to the spacecraft is to simply increase the power to the micropropulsion unit. In the 1-15W range of micropulsion, this is of comparatively lesser impact.

Endurance testing of the MicroPPT has been quite successful. Initial tests used a relatively low-technology version that still employed 2 circuits (ala the standard PPT). This design repeatedly demonstrated the ability to fire without failure for over 1 million discharges. For the pulse frequency used, this required over 10 days of continuous operation. Unfortunately this design required a dry mass in excess of the baselined TechSat21 budget which is 670g. The research then focused on more advanced designs, which used a single circuit in a low-mass configuration. After significant engineering of the propellant geometry, materials, and discharge energy a configuration was found that achieved long life. This design used a discharge in the range of 2 J to 6 J with a 6.35 mm diameter propellant. Several thrusters of this design were fired continuously for over 1 million discharges without failure.

Unfortunately, this version also exceeded the TechSat21 envelope by about 60 g.

Finally, a reduced diameter MicroPPT design has been baselined for the TechSat21; this version decreases the required discharge energy, and thereby affords significant reductions in the capacitor mass. The current estimated wet mass of the thruster is 330 grams, well below the 600-gram envelope on TechSat21. The new configuration has again demonstrated repeated long-duration operation. Development emphasis is now shifting to environmental testing. Thermal-Vacuum testing is proceeding at AFRL. Passive means are presently being used to adjust the operating temperature, however a new thermal vacuum chamber at the AFRL EP Lab is currently being characterized for active temperature control of the MicroPPT. Vibration testing is starting at the US Air Force Academy. Cadets will work with AFRL researchers to test the robustness of various proposed fabrication techniques.

Performance measurements on the MicroPPT were originally impeded by the lack of thrust measurement capability at the micronewton level. This capability was accomplished at AFRL by modifying the NASA-Glenn PPT thrust stand developed by Tom Haag⁶, to operate in a forced resonance oscillation mode. As reported at JPC 2000⁷, this technique reduced the measurement uncertainty from 10 microneutons down to 5 microneutons. Using a crude manifestation of this technique AFRL successfully measured MicroPPT thrust levels of 5 μ N/Watt during a time period in which the Teflon propellant receded 3 diameters back into the cathode shell. Based on the improved signal-to-noise using the new technique, it was expected that the thrust measurement uncertainty could be simply reduced to 0.5 microneutons. The limit at that time was uncertainties associated with the applications of the thrust, calibration weights, and a small amount of drift in the thrust stand. In the past year we have automated the NASA-Glenn PPT Thrust Stand to energize the thruster, or apply calibration weights, synchronous with the thrust stand natural oscillations. Unfortunately modifications to the thrust stand, particularly acquisition of encoded roll and pitch motors, are taking longer than expected. The thrust stand is only now undergoing final characterization prior to performing thrust measurements on the MicroPPT design baselined for TechSat21.

A series of important advances to the MicroPPT design have also been accomplished at the basic

research level in the past year. The most successful of these include:

- A technique to fire a larger propellant diameter at lower voltage. This has the engineering impact of significantly increasing the propellant throughput and reducing the risk of high-voltage failure.
- A technique to passively switch between several propellant rods. Once a given propellant rod is consumed, the MicroPPT passively switches to a second rod without switches. This has the engineering impact of significantly increasing the propellant throughput without the significant increase in dry mass and complexity that would have occurred using switches.
- Significant testing of alternate propellants containing energetic materials. Performance for these propellants looks attractive, however functionality in the MicroPPT remains an issue, as it does for any non-Teflon propellant.

TechSat21 Propulsion Flight Demonstration

A primary goal of AFRL research programs is to transfer technologies developed under USAF programs to the private sector for commercialization. The fundamental goal is to provide sufficient risk reduction to become attractive for insertion into a commercial product line, allowing USAF operational users the benefit of improved capabilities. For some technology developments, sufficient risk reduction can be accomplished using ground tests combined with modeling and simulation. For many satellite-based technologies, such as advanced propulsion, a flight demonstration is needed to retire the risk required for technology transfer. An example of this approach is the AFRL/PR development of the propulsion subsystem for the TechSat21 flight.

TechSat21 is an AFRL/VIS (Space Vehicles Directorate, Kirtland AFB, NM) mission to demonstrate sparse aperture phased array sensing from a formation of 3 microsatellites⁸. Other capabilities to be demonstrated include autonomous control, inter-satellite communications, and an array of microsatellite bus technologies such as flexible solar arrays, loop heat pipes, and micropropulsion. The mission is scheduled for launch in late 2004. The primary propulsion on TechSat 21 is responsible for the initialization of the cluster, formation keeping, and cluster reconfiguring for the one-year mission. Following an open competition, a contract was awarded in September, 2000 to a team of TRW,

Busek, and Moog to deliver a 200 W Hall thruster system for the primary propulsion, based on the design developed under an AFRL SBIR contract⁹. TRW is the prime contractor and is responsible for the systems engineering and integration, as well as the development of the power processing unit (PPU). Busek is responsible for the thruster and cathode development¹⁰, and Moog is providing the xenon feed system (XFS). Breadboard designs of all of the components have been fabricated and tested, and are performing at or above the design requirements. Coupling tests between the thruster and the XFS have also been performed to validate the flow control algorithms, and to ensure appropriate flow split between the anode and the cathode. A critical coupling test between the thruster and PPU interface was also successfully completed. Flight hardware delivery is scheduled for late 2002.

The development for the thruster and cathode is focused on transitioning the existing prototype into a flight-ready design¹¹. Thruster performance was well characterized under a preceding SBIR program, and the TechSat 21 requirements fall within the thruster's nominal capabilities, so no performance improvements are planned. As such, the major areas of development and testing performed to date have focused on lifetime and spacecraft environment design, spacecraft-thruster interactions, and fabrication and acceptance testing processes. A major part of this effort is the development of a 1/8-inch hollow cathode to a flight-ready status including over 3000 startup and thermal cycles, and stiffening of the structure in order to survive the launch environments.

The PPU development effort is focused on the buildup of a brand new system. Although the TRW team is absorbing some of the heritage from the low power breadboard PPU Busek developed as a part of another AFRL SBIR, the flight packaging and integrated tests are new efforts. The PPU portion of the program focuses on building hardware quickly in order to validate the design with the prototype and engineering model thrusters and the XFS. The XFS, on the other hand, focuses almost exclusively on COTS components with the exception of the Moog Proportional Flow Control Valve, which will control the flow rates to the thruster and the cathode through a pair of flow orifices. The primary development activity for the XFS then, is to ensure accurate, repeatable flow from the xenon tank to the engine at the low flow rates (<1 mg/sec) required for steady operation.

The attitude control for TechSat 21 was originally baselined as the Micro-PPT, and was responsible for

roll and yaw control. As the mission matured, however, the attitude control system selected more conventional reaction wheels and magnetic torque rods in order to maximize turn rates about these axes. The Micro-PPTs were converted into a technology demonstrator for the TechSat 21 mission, and were relocated to minimize spacecraft design impacts. The Micro-PPTs are being developed in-house at AFRL, and several breadboards have been fabricated and tested at AFRL (see previous section on MicroPTTs). The total mass allocation for the Micro-PPT is 660 g, and the on-orbit experiment plan will include extended firings to determine thruster performance over life, as well as validating the applicability of this thruster for primary propulsion on satellites < 25 kg, or as a replacement for attitude control actuators on larger spacecraft. Performance and life tests are planned, which will be followed by flight design, fabrication, and environmental tests.

The final part of the AFRL/PR propulsion package is a suite of sensors to measure the interaction effects of the Hall thruster and the Micro-PPT with the spacecraft¹². This suite is largely based on the success of the ESEX diagnostics¹³, but is dramatically reduced in size to accommodate the smaller mass allocation of 1.5 kg. The sensor package design is being led by JPL, includes the entire science team from the previous ESEX mission, as well as Broadreach Engineering for the flight electronics. The current baseline includes radiometers for measuring surface property effects, photometric sensors for determining the impacts on optical surfaces, a section of solar array cells, electron probes, and an ion probe. Breadboard designs for all sensor components have been successfully fabricated and independently tested during summer 2001. Testing with the interface electronics and thruster will occur later this year.

III. Mid-Power Electric Propulsion Research

High Performance Hall System

The High Performance Hall System (HPHS) program supports the development and flight qualification of a 4.5 kW electric propulsion system that includes the SPT-140 Hall thruster. AFRL and ISTI are co-funding this cost-shared contract (56% government, 44% contractor) under the auspices of the IHPRT initiative. Atlantic Research Corporation (ARC) is the prime contractor. The propulsion system includes the thruster, power processing unit (PPU), propellant management assembly (PMA), and simulated spacecraft hardware. The Experimental Design Bureau/Fakel, a Russian designer and manufacturer

of over 110 flight Hall thrusters, is developing the SPT-140 thruster. Space Systems/Loral (SS/L). Lower case leveraging their flight qualification experience with the 1.35 kW SPT-100 Hall system, is designing and manufacturing the Power Processing Unit (PPU). An existing, MOOG Inc. built, flight qualified Propellant Management Assembly (PMA) will complete the major system components. The target performance of the system is a specific impulse of 1800 s, overall system efficiency of 51%, specific mass (thruster, PPU) of 6.0 kg/kW, and a lifetime of 7200 hours. To ensure US government access to SPT-140 thruster technology, ARC will deliver a thruster design package, including engineering drawings, processes, and procedures to a US-based escrow agent.

The Fakel SPT-140 thruster preliminary design review (PDR) and critical design review (CDR) were successfully completed in December 1997 and March 1999, respectively. Due to post-CDR design changes and improvements, a delta CDR was held in May 2001. Qualification model (QM) fabrication is expected to begin in December, 2001.

In order to ensure that the SPT-140 HPHS will meet USAF requirements, an extensive series of tests is being conducted by AFRL in conjunction with other U.S.-based research and development groups. The test plans, written by ISTI and SS/L, are based on previous US SPT-100 qualification experience.

The first test series was conducted at NASA Glenn Research Center (GRC) during August 1999. The tests included measurements of the thruster performance, electromagnetic interference (EMI), and potential plume contamination. These tests were co-funded by AFRL and NASA under an Interagency Agreement. In these tests, thrust efficiency near the contractual goal of 55% was measured.¹⁴

In a second series, ground tests were performed to characterize modes of interaction between the SPT-140 Hall thruster and spacecraft components. The experiments were performed at NASA Glenn Research Center and at the University of Michigan. Measurements were made of thruster plume current density, electromagnetic interference (EMI), and surface sputtering and contamination. Diagnostics included Faraday probes, collimated sputter/deposition targets, and radio-frequency detectors. Ion current density measurements showed exponential decay with off-axis angles up to approximately 30 degrees. At off-axis angles greater than 30 degrees, results varied with chamber background pressure, presumably due to ambient

charge exchange plasma. Sputter rates of solar cell coverglass, Kapton, and RTV were accurately measured 1 meter from the thruster exit for off-axis angles less than 60 degrees. At off-axis angles greater than 60 degrees, the sputter rate was on the order of the measurement uncertainty. EMI tests found very little emission in the traditional RF communication bands. At the lowest frequencies, one band of E-field emission (10 kHz to 20 MHz) was detected which exceeded the MIL-STD-461C specification by up to 53 dB.¹⁵

A third test series at Aerospace Corporation characterized the plume from the SPT-140. A compact electrostatic ion energy analyzer was used to determine flux and energy-to-charge ratio one meter from the thruster exit. In the near field, a novel LIF system was used to map ion velocity vector between 5 and 250 mm downstream, and 200 mm radially. Accuracy of the LIF was approximately +/-150 m/s. Additionally, the thrust vector was tracked using wire probes positioned 2.2m from the thruster exit. Maximum thrust vector offset was 0.54 degrees from physical centerline.^{16,17}

The PPU PDR and CDR have also been successfully completed in November 1998 and October 1999, respectively. During testing with the breadboard unit, SS/L demonstrated an efficiency of 95.1% on the main discharge supply and a 94.4% overall PPU efficiency. PPU total mass is less than 13 kg including all required housekeeping and switching functions, modules to control the Xenon flow controllers and the cathodes, plus all required telemetry functions. The unit is capable of operating either of two thrusters via a thruster selection module.

The QM thruster and brassboard PPU will undergo an integrated life test scheduled to begin in April 2002 and continue to mid-2003. The test will consist of a simulated life of a 15-year GEO-type satellite including orbit topping and stationkeeping burns. Total thruster operation will be 7200 hours. This life test will be performed at the AFRL Electric Propulsion Laboratory located at Edwards AFB, CA. Initial checkout of the 3.3 m diameter, 8 m long Chamber 3 has been successfully completed. The xenon pumping speed, measured with NIST traceable instrumentation, was found to be 150,000 l/s with a thermal load of 7.5 kW applied. Pressure was 1.5×10^{-5} Torr during operation of the SPT-140 DM at 4.5 kW. The inside of the facility is completely lined with graphite paneling to reduce sputtering and contamination.

IV. High-Power Electric Propulsion Research

8kW Bi-Modal Hall Thruster

Busek Corp, under an AFRL Phase II SBIR, is developing a novel, high-power Hall thruster capable of bi-modal operation over a broad range of specific impulse and thrust. For bi-modal operation the thruster, while operating at constant power, should deliver continuously increasing thrust with decreasing specific impulse.

Busek has developed, constructed, and tested as 8 kW thruster and associated high-power cathode designated BHT-8000 and BHC-500 respectively. The thruster/cathode assembly was successfully tested in Busek's cryogenically pumped (T8) test facility. At 8 kW with a 300 V discharge, the thruster delivered 512 mN of thrust at 63.5% anode efficiency and 2024 seconds specific impulse.¹⁸

Very High Power Clusters of Hall Thrusters

AFRL has initiated a program to develop Hall thruster systems that operate at power levels well in excess of current state-of-the-art. The current program goal is for operation in the 100kW to 150kW range. The program addresses the AFSPC priority for orbit transfer vehicles (OTV) and rescue vehicles capable of repositioning and rescuing of marooned space assets that have failed to achieve final mission orbit. The power range is based on that expected from proposed AFRL Space Vehicle programs using deployed sails of thin-film solar arrays, and will adapt as predicted power availability changes.

During the past year, AFRL has sought to define the optimal method of approaching the mission need through discussion with industry, other government agencies and universities. The study resulted in the following design criteria:

- The high-power system should use Hall thrusters, as opposed to ion thrusters, due to their superior specific mass (2 kg/kW for Hall versus 8 kg/kW for ion thrusters)
- The high power system should be assembled from a cluster of lower power devices to reduce qualification and testing costs. A clustered system also offers the flexibility needed to meet varied power budgets on future missions. Changing the number of units in the cluster varies system power.

- The unit thruster should be a commercial flight-qualified thruster. To minimize dry mass, it should also be the highest power Hall thruster expected for GEO stationkeeping.
- An even number of thrusters should be clustered, in opposite magnetic polarity, to cancel out the Hall thruster torques.
- The unit thruster power should be sufficiently low so as to allow testing in current ground test facilities. Test facility costs for a monolithic 100kW Hall thruster could dominate the program costs.
- Based on these considerations, the unit thruster power level is expected to be in the 8 kW to 10 kW range. Hall thrusters in this range are currently in development under both NASA and AFRL programs.
- The individual Hall thrusters must be independent (i.e. no sharing of magnetic circuits or structure) so that the base units can be individually flight-qualified prior to integration into the cluster.
- Both the thruster and the PPU should be modular to minimize qualification costs. Optimal design for the propellant management system remains an open issue.

In general, the primary advantage of a clustered approach to 100 kW-class power levels concedes performance in favor of cost. The relative advantages of each approach are summarized in Table 1.

With the high power scenario determined, several technical challenges are apparent. Foremost is the ability to flight-qualify a cluster of Hall thrusters based on the qualification of each individual unit. Specific issues are:

- The effects of combined beam divergence and plume behavior on spacecraft interaction. Can the plume of the cluster be simulated from an understanding of the plume of a single unit?
- Does possible electrical cross talk through the external plasma affect the uniformity of the power distribution?
- Is the lifetime of the individual unit affected by placement within the cluster?
- Can the Hall thruster torque be effectively cancelled by assembling the cluster from an even number of thruster units?

Criteria	100 kW class Monolithic	Clustered 10 kW
<i>Performance</i>		
Efficiency	Higher	Lower
Specific Impulse	Same	Same
System Dry Mass	Lower	Higher
<i>Reliability</i>		
Thruster	About the Same	About the Same
PPU/PMA	Higher	Lower (more parts)
System Overall	Lower	Higher (redundancy)
<i>Operational Flexibility</i>		
Throttling	Lower	Higher
Orbit raise (Full power)	Same	Same
Station-keeping Suitability (Low power)	Lower	Higher
Suitability for Maneuvering/Vectoring	Lower	Higher
<i>Scalability (up and down in power)</i>		
Lower	Higher	
<i>Developmental Cost</i>	Very High	Low
<i>Test Facility</i>	Not Available/Very High	Availability/Very Low

Table 1: Trade-offs between a clustered and monolithic approach to high-power electric propulsion

- What is the optimal method of neutralizing the clustered plasma? Should the cathodes be modular, or can a single large electron source be used to neutralize the entire cluster?

AFRL has initiated a program to understand the physics and practical implications of interactions within clusters of four Hall thrusters. The clustering project will initially, experimentally characterize the interactions of the plumes with thrusters that are relatively inexpensive to operate and small enough not to require extensive vacuum facilities. In addition, by initially examining low power (200 W) thrusters, the plumes will be denser and it is anticipated that interactions will be more severe than plumes of higher power Hall thrusters. The preliminary test bed consists of four Busek Corporation BHT-200-X3 Hall thrusters in a tight packed cluster. The thrusters have been delivered and mounted into the test fixture at AFRL. Initial plume measurements have begun and results will be reported next year.

In addition to experimental measurements of thruster interactions, a significant goal of this program is to create a software tool to understand the thruster/plume interactions. In the near-term, in-house efforts are underway to use superposition of the results of current SOA axisymmetric plume models. These will be compared to the plume measurements currently underway. In the far-term, in-house and contractual efforts are preparing to create a three dimensional, unstructured grid model to simulate the interactions of an arbitrary number of thrusters. Once this cluster integration tool is experimentally validated, it will be available for users who wish to integrate clusters of arbitrary number onto spacecraft.

Currently, AFRL has contracted with Busek Corporation through a Phase I SBIR effort to design and test a 600 W Hall thruster specifically intended for use in a clustered configuration. Consideration is being given to ensure that the magnetic field of any individual thruster does not affect the operation of its neighbors. A cluster of four 600 W thrusters will then be tested in the laboratory in the 2002-03 time frame. This intermediate effort will allow for the validation of the modeling efforts as the cluster thruster size is scaled upward.

The final portion of the effort will focus on the ground validation of a cluster of 10 kW class thrusters similar in size and performance to the BHT-8000. At current power level growth rates, a cluster composed of 8 to 10 kW Hall thrusters provides good efficiency as well as flexibility in forming thruster clusters suitable for a variety of individual mission needs. A cluster of these thrusters will be designed, constructed, and tested to validate the interaction model at the 8 to 10 kW power level. With this data in hand, it will then be possible to validate the lifetime of a cluster by the life test of a single thruster. AFRL would then have a 30-40 kW cluster of Hall thrusters available for flight test in approximately 2008-09 timeframe.

Plume Investigation to understand Clustering Interactions

Another effort, in the process of being funded by EOARD, is with TSNIMASH Export, Moscow, Russia, characterizes the plume of their existing D-55 thruster. This program will investigate atomic and molecular processes in the plume region via emission spectroscopy. This effort also starts to investigate the

plume interaction issues of a clustered set of Hall thrusters for high power applications.

Power Sail

The United States Air Force is interested in increasing its presence and capability in the space environment. One major parameter that is limiting USAF missions in space is the availability of large amounts of on-orbit electrical power. To enhance this capability, the Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS) is developing PowerSail¹⁹: a two-phased program to demonstrate high power (100 kW to 1 MW) capability in space using a deployable, flexible solar array constructed of thin-film photovoltaics. Use of thin film photovoltaics in place of conventional solar arrays is projected to decrease specific mass and cost while increasing packageability. The first phase will be a proof-of-concept demonstration at 50 kW, followed by an operational system at full power. In support of this program, the AFRL Propulsion Directorate's Spacecraft Propulsion Branch (AFRL/PRSS) at Edwards AFB performed an in-house propulsion trade study in August 2000. This was a top-level trade study to optimize the propulsion system based on the perturbing forces on the array.

In order to explore design issues in more depth, AFRL/PRSS commissioned a set of external design studies of propulsion systems intended to facilitate the operation of the PowerSail array. These studies were intended to perform mission and design trades to identify potential full-power applications of PowerSail and the corresponding propulsion system requirements and design. A solicitation for the design studies was issued in October 2000. A solicitation for the design studies was issued in October 2000, for a period of performance from 4 January to 4 June 2001. The in-house trade study and the final report from Virginia Tech University will be was presented at this a recent conference in paper 2001-3346.²⁰

V. Modeling and Simulation

In October 2000, AFRL initiated a modeling and simulation effort primarily aimed at predicting the effects of electric thrusters on operational spacecraft. This effort is divided into three parts: a) electric thruster source modeling, b) plume modeling, and c) spacecraft interaction modeling. Collaborative research in these areas is with both U.S. and international scientists. International programs are funded through AFRL's European basic research organization, EOARD.

Electric thruster source modeling is currently concentrated on Hall thrusters and PPTs. Universidad Politecnica, in Madrid, Spain, has been continuing development of a one-dimensional Hall Thruster discharge model that has been useful in studying the physical relationships governing physics of Hall thruster plasmas, from the anode through supersonic expansion. Two-dimensional Hall thruster modeling using *HPHall* has continued at AFRL²¹ in conjunction with the University of Washington, the recent focus being near-wall effects. Also, an international effort is underway to compare results of *HPHall* with a similar code being developed at CNRS in Toulouse, France.

Hall thruster plume expansion models of the TechSat 21 Hall thruster are being generated by SAIC (formerly Maxwell Technologies). Their approach is to use the Gilbert 2D Toolbox, along with a Lagrangian method for main-beam expansion. At the University of Michigan, PPT ~~propellant ablation~~ ~~physics~~ is being modeled.

One of the main goals of AFRL's EP modeling and simulation effort is to integrate the results of source, plume, and surface models into a comprehensive three-dimensional model to predict thruster-spacecraft interaction. Two approaches are currently being taken to meet this goal. First, SAIC is using Environment WorkBench (EWB) to superpose the TechSat 21 Hall thruster plume onto a realistic spacecraft geometry. The result is an inexpensive, reasonable estimate of spacecraft contamination due to the Hall thruster during its lifetime, neglecting second-order interactions. The second approach, currently being evaluated, is more long term. It involves the development of new, flexible, three-dimensional plasma models that can be used with adaptive, unstructured gridding techniques. MIT is currently studying these approaches under AFOSR funding.

VI. Summary

The Air Force supports electric propulsion primarily through AFOSR, AFRL and EOARD. Overall direction for the programs comes from AFSPC, with AFRL mission analysis used to define specific technological advances needed to meet the AFSPC mission priorities. Current programs are well grouped into 3 categories defined by the thruster power level. All three agencies are currently focusing their primary research in support of the emerging USAF microsatellite missions, due to the current lack of high performance flight-qualified

propulsion at very low power levels ($P < 200$ W). Emphasis on research in the mid-power range (500W to 5kW) is diminishing with the near-term conclusion of the 4.5 kW HPHS Hall thruster development program. AFRL has recently begun to increase emphasis on very high power levels ($P > 30$ kW) through a collaborative research effort with industry.

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